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Measurement of Solar pp-neutrino flux with Borexino: results and implications

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Abstract. Measurement of the Solar pp-neutrino flux completed the measurement of Solar neutrino fluxes from the pp-chain of reactions in Borexino experiment. The result is in agreement with the prediction of the Standard Solar Model and the MSW/LMA oscillation scenario. A comparison of the total neutrino flux from the Sun with Solar luminosity in photons provides a test of the stability of the Sun on the 10^5 years time scale, and sets a strong limit on the power production by the unknown energy sources in the Sun.

1. Introduction

The solar photon luminosity $L_\odot = 3.846 \times 10^{26}$ W is measured for a precision of 0.4% [1, 2]. The energy lost by neutrinos adds $L_\nu = 0.023 \cdot L_\odot$ to this value [3]. The solar luminosity constraint on the solar neutrino fluxes can be written as [4]:

$$\frac{L_\odot}{4\pi(1a.u.)^2} = \sum \alpha_i \Phi_i \tag{1}$$

where 1 a.u. is the average Earth-Sun distance, the coefficient α_i is the amount of energy provided to the star by nuclear fusion reactions associated with each of the important solar neutrino fluxes, Φ_i. The numerical values of the α's are determined to an accuracy of 10^{-4} and better.

The estimated uncertainty in the luminosity of the Sun corresponds to less than 3% uncertainty in total solar neutrino flux.

Because of the relation (1) between the solar photon and neutrino luminosity, the measurement of the total neutrino luminosity will provide a test of the stability of the Sun at the time scale of 40000 years [5], the time needed for the radiation born at the center of the Sun to arrive to its surface. Finding a disagreement between $L_\odot$ and L_ν would have significant long term enviromental implications, and in the case of an agreement between the two measurements it would be possible to limit the unknown sources of the solar energy, different from the known thermonuclear fusion of light elements in the pp-chain and CNO-cycle.

The main neutrino sources in the Sun are the pp- and ^{7}Be reactions, providing roughly 91 and 7% of the total neutrino flux respectively. Borexino already measured the ^{7}Be neutrino flux with 5% precision [6], but till recent time the pp-neutrino flux was derived in a differential measurement using solar detectors data.

A number of projects aiming to perform pp-neutrino detection have been put forward in past two decades, but with all the time passed since the proposals, none of them started the operation facing the technical problems with realization. A possibility to use ultrapure liquid organic scintillator as a low energy solar neutrino detector for a first time was discussed in [7, 8]. The authors come to the conclusion that a liquid scintillator detector with an active volume of 10 tons is an appropriate tool to register the solar pp-neutrino if operated at the target level of radiopurity for Borexino and good energy resolution (5% at 200 keV) is achieved.

2. Solar pp-neutrino flux measurement with Borexino detector

The low-energy range, namely 165-590 keV, of the Borexino experimental spectrum has been carefully analyzed with the purpose of the pp-neutrino flux extraction [9]. The data were acquired from January 2012 to May 2013 and correspond to 408 live days of data taking.

The main features of the experimental spectrum, as can be seen in in figure 1, are: a main contribution from the ^{14}C decays at low energies (below 200 keV) and the monoenergetic peak corresponding to 5.3 MeV $\alpha-$particles from ^{210}Po decay. The statistics in the first bins used in the analysis is very high, of the order of 5×10^5events, demanding the development of a very precise model for the studies - the allowed systematic precision at low energy part should be comparable to the statistical fluctuations of 0.14%. The development of such a precise model was a main goal of the analysis.

As one can see from figure 1 the shapes of contributions to the spectrum from ^{14}C and other background components are quite different from the contribution from the expected contribution of the electron recoil spectrum from the Solar pp-neutrino. This fact allows the extraction of the Solar pp-neutrino contribution from the data.

The stability and robustness of the measured pp neutrino interaction rate was verified by performing fits varying initial conditions, including fit energy range, method of pile-up construction, and energy estimator. The distribution of the central values for pp-neutrino interaction rates obtained for all these fit conditions was then used as an estimate of the maximal systematic error (partial correlations between different factors are not excluded).

3. Results and Implications

The solar pp neutrino interaction rate measured by Borexino is $pp = 144 \pm 13(stat) \pm 10(syst)$ cpd/100 t, compatible with the expected rate of $pp_{theor} = 131 \pm 2$ cpd/100 t. The corresponding total solar pp-neutrino flux is $\phi_{pp}(Borex) = (6.6 \pm 0.7) \times 10^{10}$ cm^{-2}s^{-1}, in a good agreement with the combined best fit value of the radiochemical and other solar experiments $\phi_{pp}(other) = (6.14 \pm 0.61) \times 10^{10}$ cm^{-2}s^{-1} [10]. Both are in agreement with the expected value of $6.0 \times (1.000 \pm 0.006) \times 10^{10}$ cm^{-2}s^{-1}.

The survival probability for electron neutrino from pp-reaction is $P_{ee}(Borex) = 0.64 \pm 0.12$.

Taking into account that Borexino and other experiments measurements are independent, the results can be combined:

$$\phi_{pp} = (6.37 \pm 0.46) \times 10^{10} cm^{-2} s^{-1}.$$

The electron neutrino survival probability measured in all solar but Borexino experiment is $P_{ee}(other) = 0.56 \pm 0.08$, combining it with Borexino one we obtain:

$$P_{ee} = 0.60 \pm 0.07,$$

well compatible with theoretical prediction of the MSW/LMA model $0.561^{+0.030}_{-0.042}$.

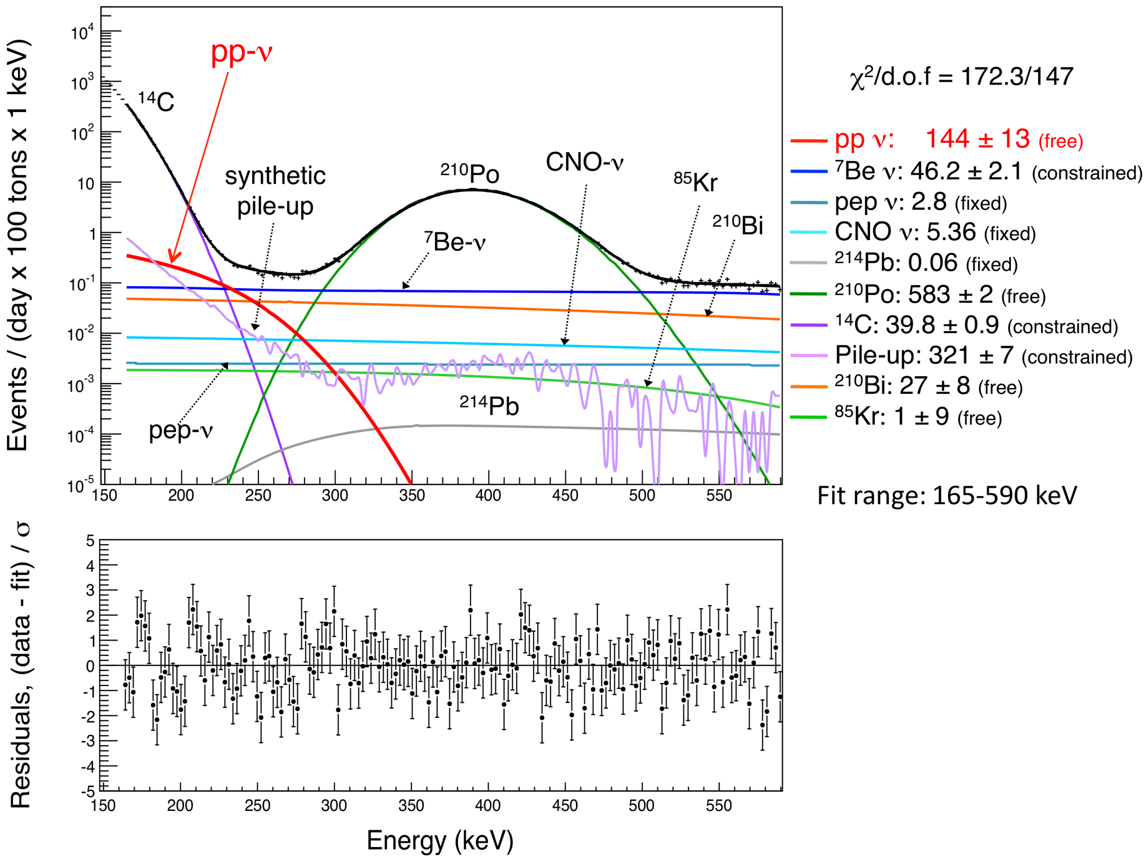

Figure 1. Borexino energy spectrum between 165 and 590 keV (in black). The pp neutrino component is shown in red, the ^{14}C spectrum in dark purple and the synthetic pile-up in light purple. The large green peak is ^{210}Po α-decays. ^{7}Be (dark blue), pep and CNO (light blue) solar neutrinos, and ^{210}Bi (orange) spectra are almost flat in this energy region.

Table 1. The Standard Solar Model predictions (for high metallicity and low metallicity abundances) and current experimental status of the Solar neutrino fluxes measurement. The limits are given for 90% C.L.. The corresponding energy release is calculated in the last column.

Reaction	GS98 [11]	AGS09 [12]	Units $cm^{-2}s^{-1}$	Measurement	MeV/1ν	L $\times 10^{26}$ W$\cdot$s^{-1}
pp	5.98 ± 0.04	6.03 ± 0.04	$\times 10^{10}$	6.14 ± 0.61 [10] 6.6 ± 0.7 [13] 6.37 ± 0.46	13.10	3.76 ± 0.28
pep	1.44 ± 0.012	1.47 ± 0.012	$\times 10^{8}$	1.6$\pm$0.3 [14]	11.92	0.009 ± 0.002
^{7}Be	5.00 ± 0.07	4.56 ± 0.07	$\times 10^{9}$	4.87 ± 0.24 [6]	12.60	0.276 ± 0.014
^{8}B	5.58 ± 0.14	4.59 ± 0.14	$\times 10^{6}$	5.25 ± 0.16 [15]	6.63	1.57 ± 0.05 $\times 10^{-4}$
hep	8.0 ± 2.4	8.3 ± 2.5	$\times 10^{3}$	< 23[16]		
^{13}N	2.96 ± 0.14	2.17 ± 0.14	$\times 10^{8}$	CNO: < 7.4[14]		
^{15}O	2.23 ± 0.15	1.56 ± 0.15	$\times 10^{8}$			
^{17}F	5.52 ± 0.17	3.40 ± 0.16	$\times 10^{6}$			

All available measurements of the solar neutrino fluxes are shown in table 1. The total energy production in the solar reactions observed till now (by detecting corresponding neutrino fluxes) is $(4.04 \pm 0.28) \times 10^{26}$ W·s^{-1} in a good agreement with a total measured $L_\odot = 3.846 \times 10^{26}$ W·s^{-1}. There is not much space left for the unknown energy sources, the 90% C.L. lower limit for the total energy production (conservatively assuming zero contribution from the not-observed reactions) is $L_{tot} = 3.68 \times 10^{26}$ W·s^{-1}. If one assumes that such an unknown source exists, its total power with 90% probability can't exceed 0.15×10^{26} W·s^{-1}. In other words no more than 4% of the total energy production in the Sun is left for the unknown energy sources, confirming that the Sun shines due to the thermonuclear fusion reactions.

4. Conclusion

Borexino provided an independent measurement of the Solar pp-neutrino flux, which can be combined with measurements from other solar experiments. A comparison of the neutrino flux from the Sun with Solar luminosity in photons provides a test of the stability of the Sun on the 10^5 years time scale, and allows to set a limit of no more than 4% of the total power production for the unknown energy sources in the Sun at 90% C.L..

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